# High efficiency diffraction grating coupler for multimode optical interconnect

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## ABSTRACT

The device presented in this paper is designed for coupling a free space optical wave under quasi-normal incidence in and out of a highly multimode waveguide with high efficiency. It uses two resonant diffraction gratings at the substrate-waveguide interface that are made of a shallow metal grating, covered with a high refractive index layer. It is shown that the resonant structure can theoretically diffract up to 90 % of the incident energy in and out of the waveguiding layer. The geometrical parameters of the structure and the tolerances can easily be achieved by conventional technology means.

Keywords : micro-optics, optical interconnect, multimode waveguide, grating coupler.

## I. Introduction

Optical interconnects enable a parallel transfer of data with high bit rates. For short distance communication like interconnects on Printed Circuit Boards (PCBs) and Multi-Chip-Module (MCM), the use of optical fibre has some disadvantages due to their intrinsic dimensions, their limited radius of curvature, the complex wiring and the size of the connectors. In this context, the development of polymers or hybrid organic-inorganic waveguides [1,2] that are compatible with planar technologies is worth investigating. Diffraction grating couplers are bound to play an increasingly important role in miniaturised systems as they bring reduced size, and have the advantage of being compatible with wafer or board scale batch planar manufacturing processes. Although they have been thoroughly investigated as a means of coupling light between free-space and single mode optical waveguides in the past[3], their potential for short distance optical data communication involving multimode waveguides has not been considered yet. Since it is generally assumed that grating coupling to multimode waveguides has a necessarily poor efficiency. It will be demonstrated here that a shallow diffraction grating can theoretically couple light very efficiently into a thick polymer layer. This approach is a possible alternative to currently developed elements in the form of 45° prism couplers fabricated one by one by laser ablation under oblique incidence[4]. This paper will explain the rationale of the multimode waveguide grating coupling concept and describe the design leading to resonant structure parameters ensuring maximum coupling efficiency of a collimated beam. The fabrication process of the resonant grating will also be described.

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## II. Structure of the grating coupler

### 2.1. Scheme of the device

This paper deals with the efficient coupling of a light beam in and out of a multimode optical waveguide, by means of a resonant diffraction grating. The device includes two gratings at either side of the waveguide (Fig. 1) for successively couple and decouple light. These gratings are identical and are used in a reciprocal configuration. The incident light impinges under quasi normal incidence ($\theta_{inc}$) on the waveguide surface where it is refracted before being diffracted in the 1$^{st}$ order of the resonant grating under angle $\theta$ such that the diffracted light can propagate in the guide. The total internal reflection condition needed for the guided propagation of the excited mode forces $\theta$ to be larger than arcsin ($n_s/n_w$) where $n_s$ and $n_w$ are respectively the substrate and waveguide indices. By taking the index values of pyrex ($n_s$ = 1.466) and an organo-silicate material[3] for the waveguide ($n_w$=1.515) at $\lambda$ = 850 nm, one finds that $\theta$ has a minimum value of 75.4°. Otherwise, one can calculate an upper limit for the grating period $\Lambda$. Indeed, in order to diffract the whole incident energy in the 1$^{st}$ order as the resonant diffraction grating does (see section 2.2), it is required that this order is the only one which can propagate except the 0$^{th}$ order. This condition leads to the following relation: $\Lambda < \lambda/n_w = 561$ nm. Knowing the upper and the lower limit of $\theta$, incidence angles in the waveguide $\theta^{w}_{inc}$ and in the air $\theta_{inc}$ can easily be deduced from the relation :

$$n_w \sin\theta = n_w \sin\theta^{w}_{inc} + \frac{\lambda}{\Lambda} = \sin\theta_{inc} + \frac{\lambda}{\Lambda} \tag{1}$$

assuming that the refractive index of air is 1. With such a structure, one can calculate the minimum and maximum angles of the in-coming or out-going beams, as shown in table 1. The range of incidence angles in air corresponds to a source of numerical aperture 0.02 illuminating the waveguide under the averaged incidence angle of –3°. If such a source can be coupled in the waveguide, it will not be uniform since the diffraction efficiency will depend on the incidence angle as will be shown in section 2.3.

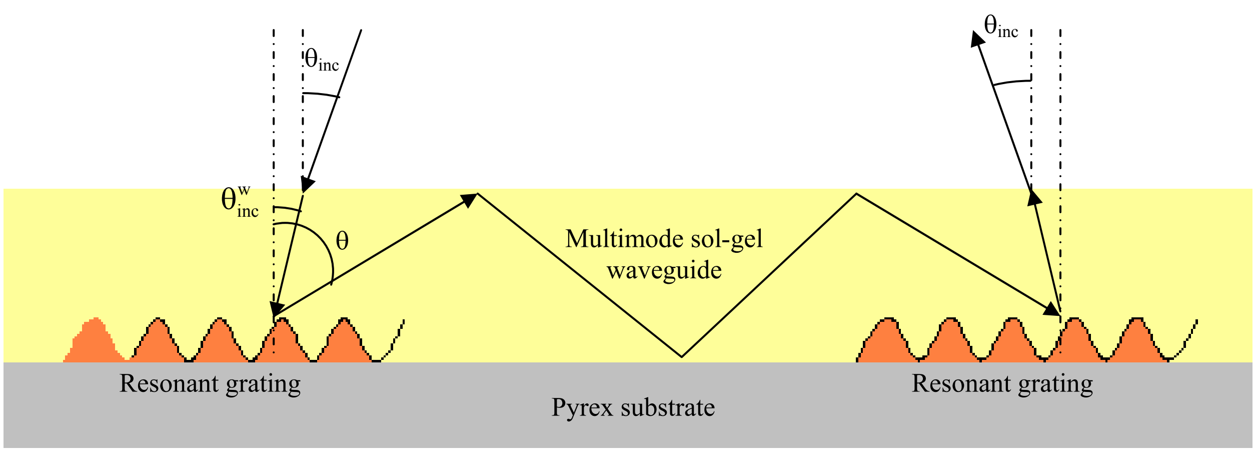



Fig. 1. Scheme of the device proposed to couple light in and out of a multimode waveguide with minimum losses

| Diffracted angle in the waveguide: $\theta$ | Incidence angle in the waveguide: $\theta^{w}_{inc}$ | Incidence angle in the air: $\theta_{inc}$ |
|---|---|---|
| 76° | -2.85° | -4.33° |
| 80° | -2.02° | -3,07° |
| 89° | -1,16° | -1.76° |

Table 1. Incidence and diffraction angles in the different media of the structure

### 2.2. Resonant grating and high diffraction efficiency

The originality of the device is to use a resonant grating structure at the bottom of the guiding layer as a coupling element. Such a structure can theoretically diffract up to 100% of the incident light in the 1$^{st}$ order[2] and, even if only 96% of the incident light is transmitted at the waveguide-cover interface, it may offer better coupling efficiency than any other grating coupler. The resonant grating comprises a corrugated mirror covered with a high index dielectric layer which is supposed to essentially replicate the corrugation as sketched in fig. 2. The mirror is metallic for cost reasons, which means that it will be a source of absorption losses in the device.

The resonance effect can be understood as follows[5]. If the refraction angle $\theta_f$ in the layer of refractive index $n_f$, the average layer thickness h and the wavelength $\lambda$ satisfy the condition

$$k_0 n_f h \cos\theta_f + \frac{\phi_m + \phi_c}{2} = m\pi \qquad (2)$$

the incident wave excites a leaky mode resonance of order m in the mirror layer[6]. The incident field is trapped in the layer with some leakage rate into the cover medium, which can be controlled by the reflection coefficient at the film-cover interface. $k_0 = 2\pi/\lambda$ is the vacuum wave number, $\phi_m$ is the reflection phase shift at the mirror and $\phi_c$ is the reflection phase shift at the layer-cover interface with incidence from the layer. In the absence of the grating there are two contributions to the Fresnel reflection: the wave firstly reflected at the layer surface, and the trapped leaky mode field re-radiating into the cover. The presence of a grating, as sketched in figure 2, modifies the balance between these two reflection contributions to the 0$^{th}$ order; furthermore, its 1$^{st}$ order represents an additional output port for the field trapped in the layer[7]. The second contribution results from a resonance. Under the hypothesis that dispersion equation (2) is fulfilled, its phase is opposite to the phase of the first contribution. There is consequently the possibility of cancelling the overall reflection in the Fresnel reflection direction by rendering the modulus of the two contributions equal. If moreover the 1$^{st}$ diffraction order is the only one which can propagate, the light has nowhere else to propagate but to be diffracted with 100% efficiency minus the metal loss since the mirror is metallic[5, 7, 8].

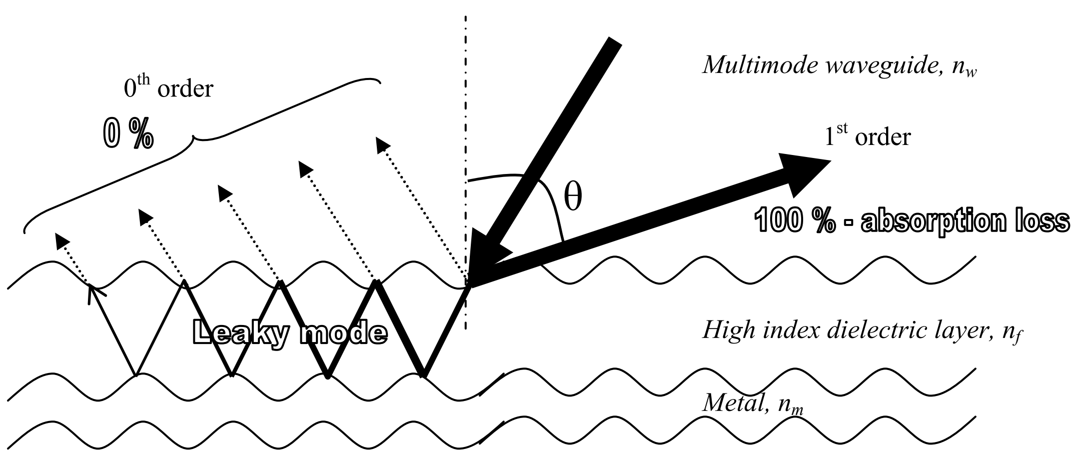


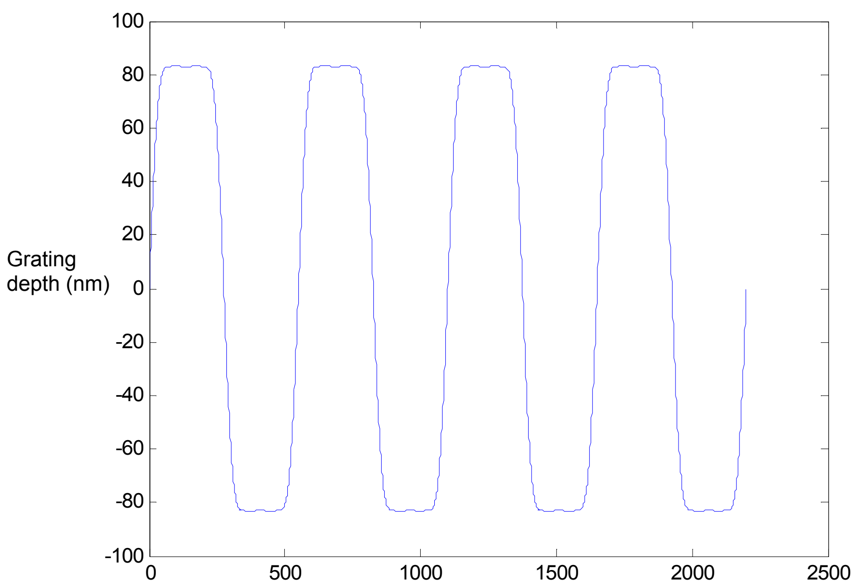

Fig. 2. : Zoom on the resonant coupling grating and scheme of the leaky mode excited in the corrugated high index layer

### 2.3. Optimised parameters

The optimisation of the resonant grating parameters is performed by means of a commercial code using the Variable Metrics Method and implementing the C method for the calculation of the diffracted field. To better fit the true grating profile, calculations are performed considering that the profile is the sum of 7 uneven sinus harmonics rather than only 1 sinus function. It allows to simulate a more rectangular profile as shown in fig. 3. In order to find the maximum diffraction efficiency, several parameters are fixed like the polarization, the direction of the incident beam, the nature of the materials according to our fabrication facilities (see table 2 for more details on the numerical values) and two parameters are optimised : the grating depth σ, which is supposed to be the same at the metal-dielectric and dielectric-sol-gel interfaces and the thickness h of the dielectric layer. Assuming that the incident beam is collimated and illuminates the resonant grating under –2.02° from the sol-gel waveguide (diffraction angle of 80° in the sol-gel), it results in a maximum diffraction efficiency of 89.6 % for σ = 169 nm and h = 122 nm. The remaining 10.3 % is absorbed by the gold substrate. These losses can be reduced by using a less absorbing metal, as silver, and another dielectric layer to decrease the confinement of the electric field close to the metal layer. This efficiency value is the best that can be achieved given the fixed parameters of table 2, but the optimised thickness and depth are not necessarily the ones which give the optimum values for other incidence angles. Fig. 4 shows the variations of the 1$^{st}$ order efficiency as a function of diffraction angle (related to incidence angle by equation (1)) in the waveguide. One can see that these variations are rather small around 80° and that the diffraction efficiency rapidly decreases for angles greater than 83°. Another optimisation could allow to increase the diffraction efficiency at grazing incidence but to the detriment of smaller diffraction angles and only to reach maximum diffraction efficiency smaller than 80%.

| Parametric quantity | Optimized parameters |
|---|---|
| Polarization : TE<br>Wavelength : 850 nm<br>Grating period : 550 nm<br>Angle of the diffracted beam in the waveguide layer: 80°<br>Metal layer : Gold, $n_m = 0.198 + i\ 5.634$<br>Dielectric layer : $HfO_2$, $n_f = 2.114$<br>Multimode waveguide : $n_w = 1.515$ | Thickness of $HfO_2$ : h = 122 nm<br>Grating depth : σ = 169 nm |

Table 2. Parameters considered for the optimisation of the resonant grating



Distance in the direction perpendicular to the grating lines (nm)

Figure 3 : simulated grating profile

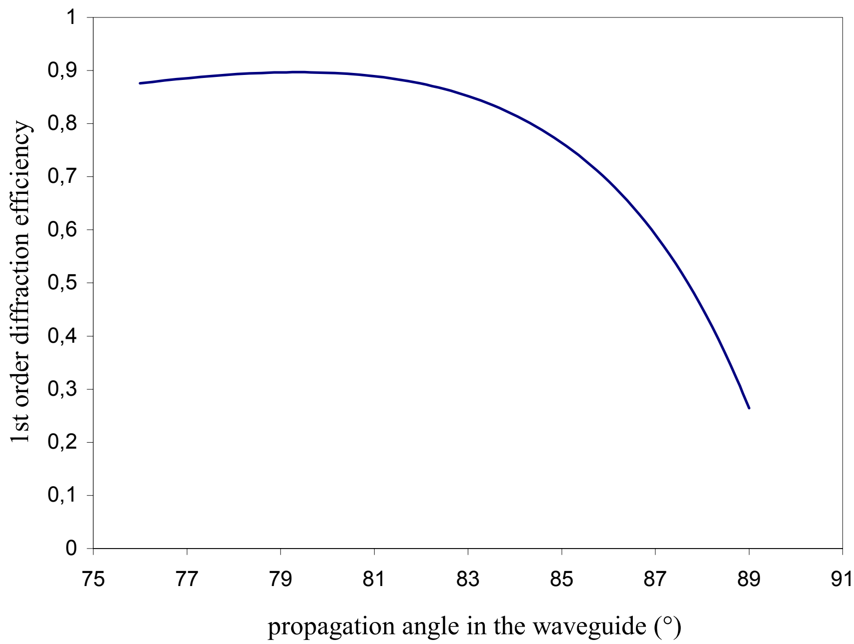



Fig. 4 : Influence of the incidence angle on the 1st order diffraction efficiency considering parameters of Table 2. Due to the reciprocity theorem, the behaviour of the in-coupling grating is the same than that of the out-coupling grating which diffracts the guided mode in the –1st order.

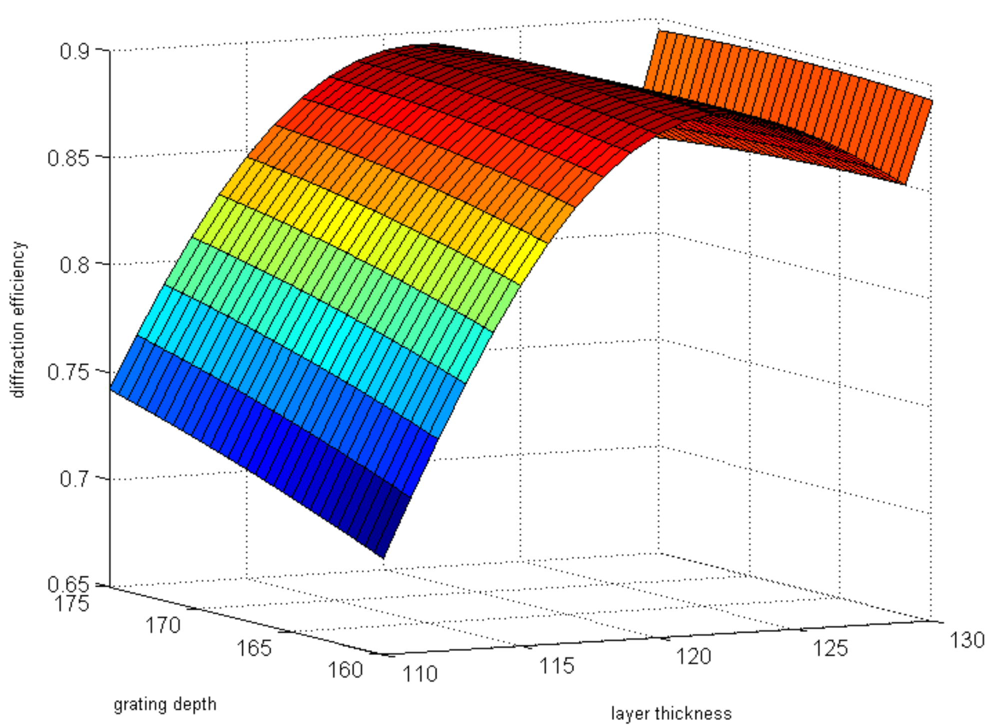



Fig. 5. : Highlighting of the grating depth and thickness layer dependency on the diffraction efficiency

The accuracy requested from the fabrication technology on the structure parameters is estimated by calculating the sensitivity of the coupling efficiency. Fig. 5 shows the influence of the grating depth and the dielectric layer thickness on the 1$^{st}$ order diffraction efficiency. It reveals a weak dependence on the grating depth from 160 to 175 nm. However, the high index dielectric layer thickness is more critical and the diffraction efficiency decreases rapidly when the thickness diminishes from the optimum (~122 nm).

## III. Preliminary experiments and discussion

The fabrication steps of the grating coupler consist of a multilayer deposition on a corugated pyrex substrate. First, a positive photoresist Shipley 505A was spin-coated on a 50 mm x 50 mm plane substrate and microstructured with a pitch of 550 nm by holographic exposure through two rectangular slits to localize the two grating couplers at both ends of the propagation area (see figure 6). The gratings were transferred into the pyrex substrate by ion beam etching. At this step a grating depth of 165±4 nm was measured by AFM (see figure 7). Then a thin titanium and gold layer is deposited on the corrugated areas only. The thin layer of titanium is applied underneath the gold layer to improve the adhesion of the gold film to the corrugated area; gold was chosen as it provides high reflectance in the near IR. The thin titanium film was sputtered and the thin gold layer was evaporated in the same vacuum chamber. Finally, a thin high refractive index layer of $HfO_2$ was deposited by an e-beam evaporation. The thickness of the $HfO_2$ is measured in situ during the deposition process by a quartz crystal thickness monitor.

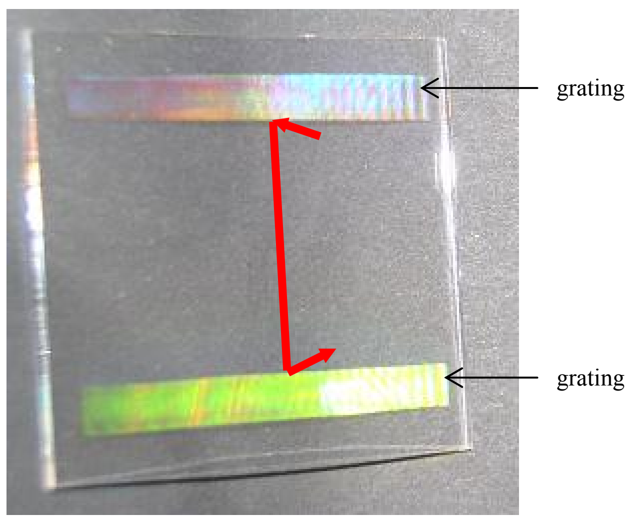



Fig. 6 : Picture of the two symmetrical gratings on a pyrex substrate

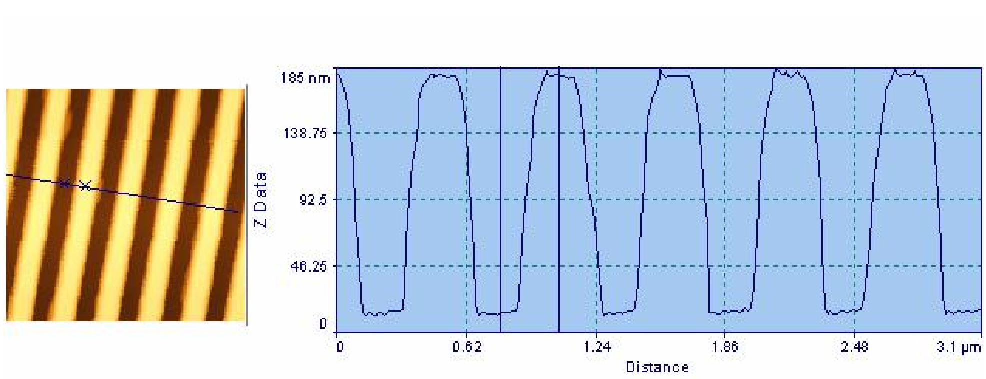



Fig. 7 : AFM image of the grating etched in a pyrex substrate

At this stage, the resonant grating structure can be used as a platform for supporting a highly multimode waveguide. In a thick waveguide layer the modal angular spectrum is practically a continuum, therefore the coupling into the guiding layer will always occur whatever the diffracted angle. The continuous modal spectrum also leads to a wide angular tolerance when coupling a diverging beam of poor spatial coherence. Two types of photo-sensitive materials will be considered in the near future to act as the optical propagation medium: a commercially available polymer and an organically modified silicate elaborated by a sol-gel process. They both have the potential of being deposited as thick layers (50 µm) that could easily support more than 30 modes on various types of substrates and present the required optical transparency and environmental stability.

## V. Conclusion

A resonant grating structure has been designed with a theoretical coupling efficiency of 90% in and out of a highly multimode waveguide. However, it is expected that the experimental coupling efficiency of the structure will be affected by the quality of the various layers. Indeed, absorption at the metal interface will occur. Surface roughness at the various interfaces will generate light scattering. Non uniformity of the thickness or refractive index in the waveguiding layer will also reduce the overall performances of the device. Nevertheless, the reasonably large tolerances on fabrication parameters that have been pointed out in the resonant grating design, make the structure a promising alternative for optical interconnect components.

It is usually believed that grating coupling to a multimode waveguide has extremely low efficiency. This is the case indeed unless a mirrored grating slab is installed at the multimode waveguide side opposite to the incident beam input side. If the mirror is multidielectric the efficiency under close to normal incidence can be 100%. In case of a simple metal mirror the efficiency can remain larger than 90%. The coupling mechanism involves the excitation of a leaky mode of the high index slab layer. The resonance width is wide therefore the fabrication tolerances are broad. One problem faced by this high efficiency coupling scheme is its polarization sensitivity. Whereas the in-coupling is likely to involve a polarized laser beam, the output grating coupler has to deal with a waveguided beam which has propagated down as 2D multimode stripe where the polarization state is not preserved. There are however ways of solving this problem at the output side. Early experiments are in progress which will tell how scattering and additional metal losses as well as the incidence conditions will affect the performances of the coupling device.

## VI. Aknowledgement

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